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COMPARISON OF THE RESULTS OF DENDROCHRONOLOGICAL MEASURING BASED ON DIFFERENT IMAGES OF A HISTORICAL WOOD SAMPLE OF SILVER FIR (*ABIES ALBA*) FROM THE CZECH REPUBLIC

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ABSTRACT

The aim of the paper was to compare the results of different methods of measuring the tree rings curve performed using different images of a reference sample made from a historical wooden con-struction of silver fir wood. The tree-ring curves were measured using two measurement methods: firstly manually on the traversing table using a stereo microscope with TSAPWin dendrochronolog-ical software and secondly in the LignoVision software (LV) from uploaded image files (scans, modified monographic scans and X-ray scans). Automatic image analysis was also tested in this software. Results showed that the tree-ring curves based on manual determination of printed-out photographs and scans using a stereo microscope on a traversing table and on manual determination of identical digital images in LignoVision matched to a large extent the data obtained by measuring the physical sample. The results were worse when tree-ring curves were measured from an X-ray scan, both using stereo microscope on a printed image, and using LignoVision. The automatic anal-ysis of the LignoVision software showed a high error rate. Finally, the results of measurements of individual image types and the possibilities of practical use of individual image records of dendro-chronological samples are discussed.

KEYWORDS: *Abies alba* (Mill.), dendrochronology, tree-ring curve measurement, non-destructive measurement, X-ray radiography.

INTRODUCTION

Measuring dendrochronological data using a microscope and a traversing table consists in meas-uring physical wood samples – either sections or dendrochronological cores samples. The archiving and storage of dated samples and the creation of their database for further use, however, may be a limiting factor for long-term operation of a dendrochronological laboratory, regarding among oth-ers the size of storage areas, storage life of samples, organization of the database etc. Creasman (2011) even emphasizes the necessity of thinking about data archiving and long-term keeping of samples with regard to the preservation of dendrochronology itself as a branch of science. Digitiza-tion of measured samples and their archiving in the form of digital databases is one of possible solu-tions. This requires high-quality capturing of all the characteristics of the physical samples. Digital images, compared to physical samples bearing complete dendrological and chemical information, can be justified as sources of information especially in case of a request for absolutely non-destructive measurement. In some cases it is impossible to take a sample, e.g. dating of artistic arte-facts or small historical wooden structures. Non-destructive methods have been more and more pre-ferred in current practice although the amount of information which can be gained using these methods is limited.

Besides standard digital images such as photographs or scans of sample surfaces, the outputs of radiographic methods and computed tomography also find their use in dendrochronological meas-urement, mainly as far as artistic, historical or archaeological artefacts are concerned. X-ray radiog-raphy measurements were dealt with by Okochi et al. (2007), who in their paper compared micro-focus X-ray computed tomography (CT) and soft X-ray radiography measurements. Similar topics were studied by Bill et al. (2012) who compared the results of measurements performed using a CT scanner developed for medical purposes and an industrial scanner. Grabner et al. (2009) prove that the X-ray CT method is more suitable for the measurement of artistic and historical artefacts than for standard dendrochronological samples taken e.g. from a roof structure. The measurement of archaeological wood samples taken together with soil and of mineralized wood samples using the X-ray CT method was tested by Stelzner and Million (2015). A different type of radiation as a tool of dendrochronology was tested by Mannes et al. (2007), who compared an image obtained using standard X-ray densitometry with a neutron radiation image.

In the case of measuring digital images using specialized software, automated measuring of tree-ring curve is an option that would speed up the whole process. Half automation of the measuring of tree-ring curve based on digital images was dealt with by He et al. (2008); the possibilities of speed-ing up the process of obtaining dendrochronological data by using measurement automation were also tested by Fonti et al. (2009). Automatic reading of tree-ring curves from CT outputs was the goal of Entacher et al. (2007).

With the exception of X-ray and CT scanning, most samples require some kind of surface treat-ment in order to remove impurities and unevenness and to increase the contrast between early and late wood (e.g. Sass and Eckstein, 1994, Spiecker 2000, Gärtner and Nievergelt 2010). New surface treatment methods are currently being developed in addition to standard ones (Spiecker 2000, Gärt-ner and Nievergelt 2010). X-ray and CT scanning methods do not require demanding sample prepa-ration processes and their use satisfies all requirements for non-destructive testing of historical arte-facts (e.g. polychrome sculptures).

The contribution of the paper consists in comparing simple, available and mobile methods of obtaining digital images of the reference samples of silver fir (*Abies alba* Mill.) for the measuring of dendrochronological data. The silver fir was chosen because of its great importance for the measurement of historical wooden structures in the Czech Republic, effortless readability of its tree-ring curve and the existence of standard tree-ring chronology for the Czech Republic area.

MATERIALS AND METHODS

A reference sample was cut out from a beam that forms part of the historical timber ceiling struc-ture in the Ropice Castle (Frýdek-Místek region, Czech Republic) which is made of silver fir wood (*Abies alba* Mill.), one of the dominant wood species in historical wooden structures in the Czech Republic (Vinař 2010).

The sample was cut across the grain in radial direction. The dimensions of the sample were 210 × 190 × 80 mm (width × height × length); the humidity of the sample was 8.65 % at the time of measurement. The surface of the sample was finished by plane.

The sample we used for the study was chosen for its distinctive tree rings and its absence of wood faults and defects, as well as absence of false or missing tree rings. The sample had also already been compared with standard tree-ring chronology for the Czech Republic and dated by dendro-chronological laboratory DendroLab. The obtained data were evaluated and successfully compared with a standard chronology; the sample was dated back to 1774. The successful comparison of the curve measured on a physical sample with standard chronology validated this curve as a reference one for other measurement methods used by authors.

Student's t-test and Baillie-Pilcher and Hollstein correlation methods were selected for the corre-lation of data in this study (Baillie and Pilcher 1973; Hollstein 1980; Cook and Kairiukstis 1990).

Next to Student's t-test, Baillie-Pilcher and Hollstein correlation methods, another methods for scoring how well two samples match at a certain overlapping position were used. One of them was the Gleichläufigkeit. The Gleichläufigkeit score is based on counting how well the two tree-ring curves have followed each other in comparing at a certain overlapping position. If both tree-ring curves trend matches, it gives a plus point, the difference gives a minus point. The sum of these points divided by the number of years compared, gives the Gleichläufigkeit index. The other meth-od called % CC - degree of overlapping of the growth ring curves being compared - expresses the percent accord of tree-ring curves tendency. In dendrochronology two main concepts are used to express the quality of accordance between time series: Gleichläufigkeit and/or t-values. While the t-statistic is a widely known test for correlation significance, Gleichlaeufigkeit was developed as a special tool for cross-dating of tree-ring series (Eckstein and Bauch 1969). These concepts are char-acterised by a different sensitivity to tree-ring patterns. While Gleichlaeufigkeit represents the over-all accordance of two series, t-values are sensitive to extreme values, such as event years. A combi-nation of both is realized in the Cross-Date Index (CDI). Since the CDI is a very powerful parame-ter in cross-dating, the possible matches are ordered by descending CDI in the output. (Dating-Index cf. Rinn 2011)

Photography and scanning of the sample

First of all, the sample was marked, documented and photographed with high resolution (Fig. 1); the photographs were made using a Nikon D5100 digital camera with a Nikon AF-S NIKKOR 18-55 mm f/3.5-5.6G VR lens. The resolution of recorded photograph was 3264 x 4928 pixels. Then the sample was scanned using a standard office scanner HP LaserJet Pro 200 color MFP M276nw. The resolution of recorded scan was 9924 x 14039 pixels. The resulting scan (Figs. 1 and 2) was also saved as a monographic image (Fig. 3). The obtained monographic image was further modified to black and white image for better resolution of the boundaries of the annual rings by enhancing contrast.

Fig. 1: Photograph, scan (with measurement path) and X-ray scan of the sample of Abies.

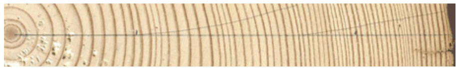

Fig. 2: Measured part of the sample with measurement paths for LignoVision.

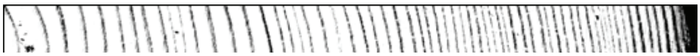

Fig. 3: A part of the scan saved as a monographic image.

Fig. 4: Measured part of the X-ray image with measurement paths for LignoVision.

X-ray diagnostics and scanning of the sample

An X-ray image of the sample (Figs. 1 and 4) was made using a mobile high-frequency X-ray scanner EcoRay HF 1040. As there is no portable specialized X-ray scanner for wood, a scanner designed for veterinary purposes was used. The electrical exposure voltage of the device is 40–100 kV with an electrical charge of 0.32–100 mAs; the dimensions of the scanner's focal point are 1.2 × 1.2 mm and exposure times vary between 0.02–2.5 s. The mobile device with dimensions of 344 × 191 × 188 mm works with a DDR image receptor (X-ray panel, Fig. 5 on the left) to ensure direct digitization of samples into digital X-ray images. Previous measurements have shown that the best results for dried-out historical fir wood are achieved for exposures at 40 kV and 10 mAs. The resulting image had a resolution of 1280 × 1412 pixels.

Fig. 5: X-ray scan device EcoRay HF 1040 and measuring of the sample.

The measurement path was the same for all cases (Fig. 1) and for all image types in order to eliminate any deviations in the measured tree-ring curves that would occur if different paths were measured on one sample. Only one sample was measured in order to obtain demonstrable compari-son of measurement results achieved using various methods. The sample was selected from a large set of 20 samples as the one with the largest ring curve, no wood faults or defects and no false or missing tree rings, which suggested maximum measurement success rate among all available sam-ples.

Measurement methods

The tree-ring curves were measured along the selected path using two measurement methods: 1) manually on the traversing table using a stereo microscope and 2) in the LignoVision software (LV) from uploaded image files (scans, modified monographic scans and X-ray scans). The meas-urement accuracy was 0.01 mm. Each of final tree rings curves was summarised from 10 basic curves along the selected path on each one sample or image. The number of basic curves was chosen to eliminate human error factor.

In case of the manual measurement using stereo microscope the data were recording in the TSAPWin software with a measurement accuracy of 0.01 mm. Using a stereo microscope, data were read directly from the sample, from a printed photograph of the sample, from a printed scan of the sample and from a printed X-ray scan of the sample. All images were printed with a standard resolution using an office printer which was 600x600 dpi for both colour and monochromatic print.

Data obtained by the LV software were uploaded first with manual determination of tree-ring boundaries, later also with automatic analysis of tree-ring boundaries and curves. The automatic analysis of the images was performed using a special algorithm of the LignoVision software. The scan of the sample was selected as the digital image used for automatic analysis because it had the highest quality. In the first step, LignoVision analysed the contrast spectrum of the image along a line selected manually by the user (Fig. 10). In the second step, the assumed tree-ring boundaries were marked; based on the detected boundaries, the tree-ring curves were measured and displayed in the form of dendrochronological curves. In the case of the adjusted monographic scan, parasitic noise in early wood areas was removed by increasing contrast (Fig. 8).

RESULTS

Using the methods described above, we obtained a total of 10 sets of measured data (summary tree-ring curves, each obtained from 10 basic measurement curves along the measured line on each one sample or image). In the first step, the measured data sets in the form of dendrochronological curves were compared with each other using the TSAPWin software.

The total length of path measured on a sample was 116.97 mm; the minimum measured tree-ring curve was 0.61 mm; the maximum measured tree-ring curve was 4.62 mm; the average tree-ring curve was 1.77 mm.

Tab. 1: The overview of all studied measurement methods and the resulting tree-ring series' codes.

Measurement methods	TSAPWin	LignoVision (LV)		LignoVision - automatic analysis	
Wood sample	S1				
Photography image	S2a	S2b			
Scanned image	S3a	S3b	S3c	S3d	S3e
X-ray image	S4a	S4b			

Comparison of curves from manual microscope measurement

The tree-ring curves based on manual determination of printed-out photographs and scans using a stereo microscope on a traversing table and on manual determination of identical digital images in LignoVision matched to a large extent the data obtained by measuring the physical sample. The differences between the measurement results of the sample itself and of its photograph were negli-gible in both cases. The final results were not even distorted by the varying scales of the photo-graphs, the scan and the physical sample as there are scale setting and data correlation options in the dendrochronological programs. The correspondence of the data sets was verified using cross-dating indices, the cross dating being performed in TSAPWin. The results were worse when tree-ring curves were measured from an X-ray scan, both using stereo microscope on a printed image, and using LignoVision.

Tab. 2: Comparison of results of microscope and LignoVision measurements of different images with the reference measurement of the sample (S1).

Sample	Ref.	OVL	Glk	GSL	% CC	TV	TVBP	CDI	TVH
S2a	S1	66	82	***	98	36.2	14.4	118	14.5
S3a	S1	66	85	***	98	37.0	14.1	121	14.2
S4a	S1	62	75	***	93	20.3	7.1	55	7.4
S2b	S1	66	81	***	98	38.5	13.2	111	14.2
S3b	S1	65	86	***	98	44.0	14.9	150	20.0
S3c	S1	62	85	***	97	32.2	10.5	97	12.2
S4b	S1	64	45	*	84	12.1	1.4	9	1.5

Legend: Ref. – reference sample; OVL – number of growth rings of curve overlapping; Glk – the Gleichläufigkeit score; GSL – level of significance of the Gleichläufigkeit coefficient; % CC – degree of overlapping of the growth ring curves being compared; TV – T-test value; TVBR – T-test value according to Baillie and Pilcher (1973); CDI – cross dating index; TVH – T-test value according to Hollstein (1980).

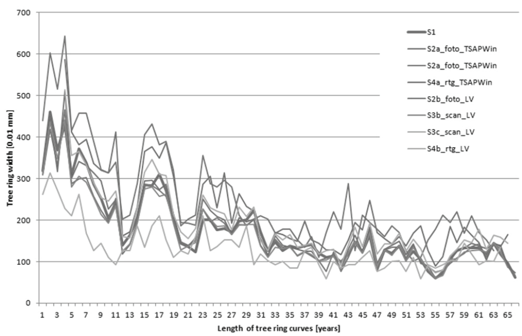

Fig. 6: Collective diagram of summary curves obtained from all manual microscope and from all manual LignoVision measurements.

The distortion of tree-ring curves in X-ray images, caused by the image resolution, can be sup-pressed e.g. by better contrast settings, image quality and other factors. Growth defects and devia-tions from the ideal axis of trunk growth have essential influence on the sharpness of the tree-ring boundaries. Such defects can be minimized by reducing the sample dimension in the axis of the X-ray beam (sample thickness).

At the same time, it is evident from the cross dating results that the differences in accuracy be-tween photograph, scan and monographic scan measurements are not significant and were probably caused by manual determination errors rather than by the parameters of the images measured.

Comparison of curves from automatic measurements in LignoVision

First of all, the scan of the sample was automatically analysed without being previously altered (S3d). Then the analysis was repeated on an altered monographic scan (S3e). Other image types were not used due to their worse results in previous measurements.

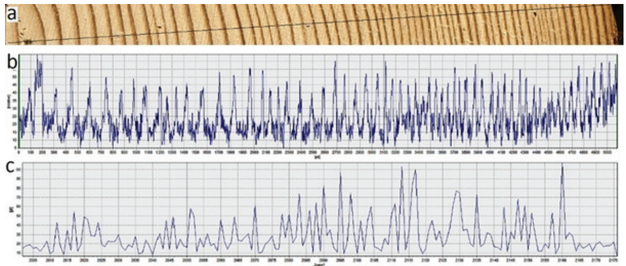

Fig. 7: Automatic analysis in LignoVision based on unaltered scan of the sample: a) digital scan image, b) contrast spectrum, c) resulting growth ring curve (S3b_scan_auto) – axis labels: horizontal label for years and vertical for tree ring width.

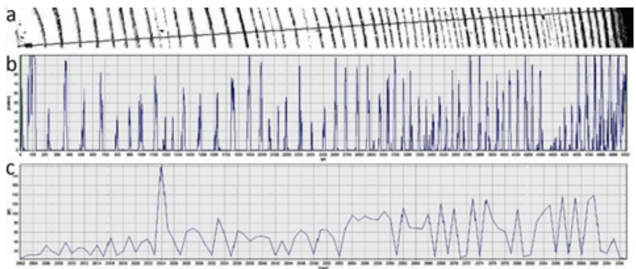

Fig. 8: Automatic analysis in LignoVision based on altered monographic scan of the sample: a) digital monographic scan image, b) contrast spectrum, c) resulting growth ring curve (S3c_scan_auto) – axis labels: horizontal label for years and vertical for tree ring width.

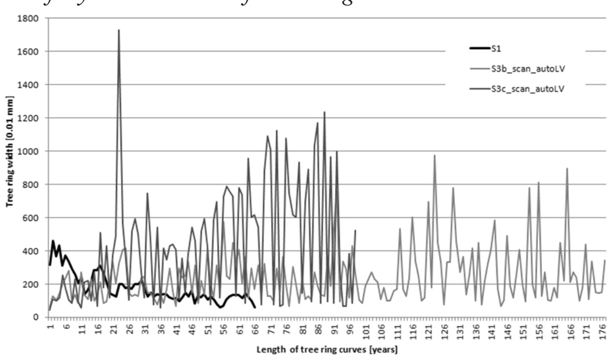

Fig. 9: A collective diagram of summary curves obtained from LignoVision automatic measurements on normal and monographic scan.

As we can see from the comparison of the curves from automatic analyses with the reference tree-ring curve (Fig. 15), the automatic analysis of the LignoVision software shows a high error rate. Neither the number of detected tree-rings nor their curves corresponded to the reference meas-urement, even in the case of the monographic scan (S3e).

Although LignoVision enables manual adjustment or deletion of incorrectly detected tree-ring boundaries after the automatic analysis, this process is more time-consuming than manual determi-nation due to the high error rate of the automatic analysis.

DISCUSSION

The accuracy of the results of manual determinations of the printed photograph (S2a) and scan (S3a) using a stereo microscope, a traversing table and TSAPWin is similar to the accuracy of the result of the measurement performed on the physical sample (S1). To a small extent, measurement errors were caused by a different quality of digital and printed images; much more errors, however, were caused by human factor during manual setting of the boundaries of individual tree-rings. The same conclusions can be made for manual determinations of digital images using LignoVision. The measurements of the scan of the sample (both colour (S3b) and monographic (S3c)) showed the smallest deviation from the reference data measured on the physical sample; therefore, scanning the sample seems to be the best method for obtaining digital images as regards quality of these images. At the same time, the effect of possible geometrical distortion by the camera lens is removed if a cross section is scanned.

Worse results are achieved by measuring X-ray or CT scans due to their low contrast and distor-tion of tree-ring boundaries, as was also confirmed by other authors. Bill et al. (2012) compared the measurement results of a CT scanner developed for medical purposes and an industrial scanner; only the industrial scanner delivered satisfactory results. The next part of their experiment consisted in measuring dendrochronological data using CT from archaeological oak wood; however, they were not successful with this type of sample due to the low contrast of the images. Grabner et al. (2009), on the other hand, have proven the suitability of the X-ray CT method for the measurement of artistic and historical artefacts; for larger artefacts, however, they consider the measurement problematic due to distortion of tree-ring boundaries. Stelzner and Million (2015) state that the quality of the resulting data depends more on the contrast of the wood than on the technical charac-teristics of the scanning equipment. A different type of radiation as a tool of dendrochronology was tested by Mannes et al. (2007), who compared an image obtained using standard X-ray densitome-try with a neutron radiation image. Both methods would lead to comparable data, but only samples of little thickness were irradiated. The authors recommend using the neutron method only as sup-plementary to the standard X-ray method, regarding the varying sensitivity for different chemical elements.

To emphasize the contrast of tree-ring boundaries, the digital images can be processed in various software environments. Monochromatic processing is the method most frequently used.

To emphasize the tree-ring boundaries, Machado et al. (2013) tested a Geographic Information System (GIS) program for creating contour lines. Although satisfactory results were achieved, the authors state that a more detailed analysis of specific computer programs and specially trained oper-ators would be necessary for their method.

According to the authors' results, the distortion of tree-ring boundaries is directly proportional to the thickness of sample to be X-rayed when radiographic methods or computed tomography are used. It is, however, not possible to reduce the thickness of the sample without destructing the arte-fact. This limitation of 2D images in X-ray computed tomography was solved e.g. by Van den Bulcke et al. (2014), who programmed 3D images of samples in MATLAB, thus achieving angular and directional correction in tree-ring curve measurements. They also dealt with automatic analyses of tree-ring curves, but the success of the analyses depended on the accentuation of the tree-rings. The automatic measurement of tree-ring curves in LignoVision used by the authors of this paper showed not to be functional, both for the unaltered scan and for the altered monographic scan in which the increased contrast of the tree-ring boundaries could lead to sufficient accuracy of the measurement. However, due to the natural characteristics of the wood mass, automatic tree-ring detection was not successful and it cannot be used even with subsequent manual adjustments as these adjustments are exceedingly time-consuming.

CONCLUSIONS

The manual determination from printed templates of a photograph and a scan by means of a ste-reo microscope, a traversing table and the TSAPWin software resulted in a significant conformity of measured data with data measured using the same method on a physical reference sample. The measurement accuracy depends on the quality of a digital image as well as on the print quality. Measurement deviations can also be caused by measurement errors caused by the human factor dur-ing manual entry of boundaries of individual tree-rings. Nonetheless, this measurement verified the possibility to successfully measure tree-ring curves from digital templates only, at the absence of a physical sample and software for measuring digital templates.

During the manual measuring of tree-ring curves from digital templates of a photograph and a scan of the sample in LignoVision software, the presumption for the need for a quality digital image was confirmed. The lowest deviation from reference data measured on the physical sample was detected in the measurement from a sample non-edited scan. Measurement results on the mono-graphic scan showed lower accuracy even after increasing the contrast of the scan. The error could be caused by distortion. The tree-ring curve measurement from outputs from the mobile X-ray equipment was included in the research due to the requirement for non-destructive measurement in case of archaeological and historical artefacts directly in the terrain or at restoration shops. The res-olution of X-ray images from the X-ray scanner EcoRay HF 1040 used by the authors showed to be insufficient at the exposure with the voltage of 40 kV and 10 mAs for dendrochronological dating. The image quality was limited both by the maximum exposure voltage of the device, and especially by the dimensions of the sample, when unlike CT methods, X-ray screens through the whole sample and not only individual cuts.

The automatic measurement of dendrochronological data from digital templates from LignoVision was not successful, where the main obstacle to measurement accuracy seems to be natural parameters of wood mass, such as variable colour at the transfer of the spring and summer wood and the contrast of tree-rings. The automatic detection of tree-rings in this software was unable to determine even the correct number of tree rings.

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